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Coulomb drag in double layer systems with correlated disorder

I. V. Gornyi†, A. G. Yashenkin‡ and D. V. Khveshchenko§
† Ioffe Physico-Technical Institute, St Petersburg, Russia
‡ Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg 188350, Russia
§ NORDITA, Blegdamsvej 17, DK-2100 Ø, Copenhagen, Denmark

Abstract. We study the effect of correlations between impurity potentials in different layers on the Coulomb drag in a double-layer semiconductor electron system. It is found that for strongly correlated potentials the drag in the diffusive regime is considerably enhanced as compared to conventional predictions. The appropriate experimental conditions are discussed, and the new experiments are suggested.

Introduction

Over the past decade the frictional drag in double-layer two-dimensional electron systems has been a subject of extensive experimental [1] and theoretical [2, 3, 4] studies. This phenomenon is manifested in the appearance of current I_2 or voltage V_2 in the "passive" layer 2 when the applied voltage V_1 causes the current I_1 to flow in the "active" layer 1. The strength of the drag is characterized by either transconductivity $\sigma_{21} = (I_2/V_1)_{V_2=0}$ or transresistivity $\rho_{21} = (V_2/I_1)_{I_2=0}$, which are related one to another as $\rho_{21} = -\sigma_{21}(\sigma_{11}\sigma_{22} - \sigma_{12}\sigma_{21})^{-1} \approx -\sigma_{21}\sigma_{11}^{-2}$ where σ_{ii} are the intrinsic conductivities of the layers.

In the absence of tunneling, the drag arises due to interlayer momentum transfer mediated by inelastic scattering (mainly, Coulombic) of carriers that belong to different layers. In the conventional theory [2], the carriers in each layer are scattered by their own impurity potentials. As a result, the processes contributing to σ_{21} can be understood in terms of coupling between *independent* thermal density fluctuations in different layers. The phase space available to the thermal excitations is small and limited by energies $\omega < T$. Therefore, the drag effect rapidly vanishes with decreasing temperature. For instance, $\rho_{21} \propto T^2$ ($T^2 \ln T$) in a clean (dirty) normal metal [2] and $\rho_{21} \propto T^{4/3}$ for composite fermions in double-layers of electrons in the half-filled Landau levels [3]. However, the recent experiments [5] have demonstrated that the transresistivity does not vanish at low temperatures.

The picture of independent impurity potentials used in Refs. [2, 3] is well justified in the case of the standard experimental geometry [1], where two Si delta-doped layers (DDLs) are situated on the outer sides of the double quantum well. The DDLs not only serve as the reservoirs supplying carriers but also introduce disorder in the form of a smooth random potential (SRP) of the ionized donors. Moreover, due to the efficient screening the carriers in each quantum well experience only a SRP created by the nearest DDL.

Instead, one can consider an alternative geometry where a single DDL is located in the middle between the two electron layers, so that the SRPs in both layers are almost identical. This setup gives one an opportunity to study a new type of coherent effects in systems with spatially separated carriers. This case is obviously beyond the conventional theoretical description [2, 3].

In the present work we investigate the influence of correlations between the impurity potentials in different layers on the transresistivity. We focus our attention onto the case of a long characteristic time, τ_g, at which the carriers feel the difference between the SRPs in the two layers ($\tau_g \gg \tau_{tr}$, where τ_{tr} is the transport scattering time in each layer). We show that in this case the drag is strongly enhanced in comparison to the non-correlated situation. This enhancement is due to a possibility of a coherent motion of carriers propagating in different layers and feeling nearly the same random potential. As a result, the effective time of their interaction increases considerably. This gives rise to the new behavior of the transresistivity

$$\rho_{21}^{\text{corr}} \simeq -\frac{\pi^4}{24}\frac{\hbar}{e^2}\frac{\ln(T\tau_g)}{(k_F d)^4(\kappa l)^2}, \quad \tau_g^{-1} \ll T \ll \tau_{tr}^{-1}, \tag{1}$$

$$\rho_{21}^{\text{corr}} \simeq -\frac{\pi^4}{6}\frac{\hbar}{e^2}\frac{(T\tau_g)^2}{(k_F d)^4(\kappa l)^2}, \quad T \ll \tau_g^{-1}. \tag{2}$$

Here, $l = v_F\tau_{tr}$ is the electron mean free path, k_F (v_F) is the Fermi momentum (velocity), d is the interlayer distance (throughout this paper we assume $l \gg d$), and κ is the Thomas-Fermi momentum. This term yields the dominant contribution to ρ_{21} within the entire experimentally accessible temperature range, provided that the system remains in the diffusive regime, $T \ll \tau_{tr}^{-1}$. We specify the experimental conditions necessary for the observations of the behavior described by Eqs. (1) and (2), and predict a suppression of these regimes by a weak magnetic field.

Calculations

The new correlation effects for the transconductivity are described by diagrams with two electron loops (one current vertex per each), connected not only by the interlayer Coulomb interaction lines but also by the impurity lines combining into the interlayer Diffusons and Cooperons. After the summation over electron frequencies and momenta, the non-zero contribution of these diagrams to the DC transconductivity takes the form

$$\sigma_{21}^{\text{corr}} = \frac{4e^2}{\pi\hbar T}\int\frac{D(dq)}{Dq^2+\tau_g^{-1}+\tau_\varphi^{-1}}\int_0^\infty\frac{d\omega}{\sinh^2\frac{\omega}{2T}}\,\mathrm{Im}\Psi_c(\mathbf{q},\omega)\,\mathrm{Im}\Lambda_c(\mathbf{q}.\omega), \tag{3}$$

The quantities Ψ_c and Λ_c are given by

$$\Psi_c(\mathbf{q},\omega) = \psi\left(\frac{Dq^2-i\omega+\tau_g^{-1}+\tau_\varphi^{-1}}{4\pi T}+\frac{1}{2}\right),$$

$$\Lambda_c(\mathbf{q},\omega) = 2\left[\ln\frac{\varepsilon_0}{T}+\lambda_{21}^{-1}-\Psi_c(\mathbf{q},\omega)+\psi(1/2)\right]^{-1},$$

where ψ is the digamma function, $\varepsilon_0 \propto \varepsilon_F$ is the upper energy cutoff, τ_φ is an inelastic phase-breaking time, and λ_{21} is the effective interaction constant:

$$\lambda_{21} = (4\pi^2\nu_F)^{-1}\langle V_{21}(\mathbf{p}-\mathbf{p}')\rangle_{\mathbf{p},\mathbf{p}'}.$$

Assuming that the screening is strong enough, $\kappa d \gg 1$, and $k_F d \gg 1$, one finds $\lambda_{21} \simeq \pi(4k_F d\kappa d)^{-1}$.

Evaluation of the integrals in Eq. (3) yields

$$\rho_{21}^{\mathrm{corr}} \simeq -\frac{2\pi^2}{3}\frac{\hbar}{e^2}\frac{1}{(k_{\mathrm{F}}l)^2[\lambda_{21}^{-1}+\ln(\varepsilon_0/T)]^2}\ln\frac{T\tau_\varphi\tau_g}{\tau_\varphi+\tau_g} \tag{4}$$

at $\tau_g^{-1} \ll T \ll \tau_{\mathrm{tr}}^{-1}$, and

$$\rho_{21}^{\mathrm{corr}} \simeq -\frac{8\pi^2}{3}\frac{\hbar}{e^2}\frac{(T\tau_g)^2}{(k_{\mathrm{F}}l)^2[\lambda_{21}^{-1}+\ln(\varepsilon_0\tau_g)]^2} \tag{5}$$

at lower temperatures. These equations constitute our main result. Under realistic experimental conditions (see below) the value of λ_{21}^{-1} is sufficiently large for one to neglect the logarithmic terms in the denominators of Eqs. (4) and (5). Also, since the interlayer decoherence time τ_g is temperature independent, the argument of the logarithmic function in the numerator of Eq. (4) is linear in temperature provided that $\tau_g \ll \tau_\varphi$. Then Eqs. (4) and (5) reduce to Eqs. (1) and (2), respectively.

Discussion and experiments

Now let us compare these equations with the results of the standard theory [2]:

$$\rho_{21}^{\mathrm{conv}} = -\frac{\hbar}{e^2}\frac{\pi^2\zeta(3)}{16}\frac{1}{(k_{\mathrm{F}}d)^2(\kappa d)^2}\left(\frac{T}{\varepsilon_{\mathrm{F}}}\right)^2. \tag{6}$$

We see that at $T \ll \tau_{\mathrm{tr}}^{-1}$ our result exceeds the conventional one: in the interval $\tau_g^{-1} \ll T \ll \tau_{\mathrm{tr}}^{-1}$ the correlation effects lead to the smoother T-dependence, while at $T \ll \tau_g^{-1}$ the prefactor of the T^2-dependence is $(\tau_g/\tau_{\mathrm{tr}})^2$ times greater in our case.

The expression (3) resembles the Maki-Thompson correction to the conductivity of a single-layer system [6]. However, in that case the corresponding processes yield a small correction to the Drude term while in the double-layer system they determine the leading contribution to σ_{21}. Also, in our situation there exists the temperature-independent quantity τ_g resulting in a new behavior at $\tau_g \ll \tau_\varphi$ and $T \ll \tau_g^{-1}$.

The origin of the interlayer decoherence time τ_g can be explained as follows. Consider two coherent electron waves propagating in slightly different random potentials ($u+\delta u$ and $u-\delta u$). After passing through the distance of order of the SRP correlation length a they acquire a random phase difference $\Delta\phi \sim (2\delta u)v_F^{-1}a$. This leads to the electron's phase diffusion with the diffusion coefficient $D_{\mathrm{ph}} = (\Delta\phi)^2 v_{\mathrm{F}} a^{-1}$, and provides a complete loss of phase coherence over the time $\tau_g \sim D_{\mathrm{ph}}^{-1}$.

A perpendicular magnetic field leads to a suppression of the transresistivity, since one has to replace τ_g^{-1} by $\tau_H^{-1} = 4DeH/(\hbar c)$ in Eq. (1) at $\tau_g^{-1} \ll \tau_H^{-1} \ll T$ and in Eq. (2) at $T, \tau_g^{-1} \ll \tau_H^{-1}$.

Now we discuss the experimental conditions under which the above theory applies. For the standard geometry we have found that the condition $\tau_g \gg \tau_{\mathrm{tr}}$ can never be satisfied as long as $\kappa d > 1$. We note, however, that unavoidable substrate roughnesses may lead to the *correlated* interface roughnesses of both quantum wells, thanks to the long-range character of the deformation field. Then in very clean samples where the interface roughness becomes the main scattering mechanism one can expect some coherence of the kind described in this work to occur even in the conventional geometry.

The situation is different for the suggested geometry with a single DDL located *between* the two quantum wells. Introducing a finite width of the DDL δ we find that the condition $\tau_g \gg \tau_{\rm tr}$ can be rewritten as $2(k_{\rm F}\delta)^2 \ll \min[1, \kappa d]$. For $\kappa \sim 0.02$ Å^{-1}, $k_{\rm F} \sim 0.015$ Å^{-1}, $\delta \sim 10$ Å, and $d \sim 400$ Å the above criteria are fulfilled, and there exists the regime of temperatures described by Eq. (1). Note that it might be easier to observe this regime in dirty samples (yet with $l \gg d$). For $l \sim 5000$ Å (which implies $\tau_{\rm tr}^{-1} \sim 4$ K and $\tau_g^{-1} \sim 0.2$ K) Eq. (1) yields ρ_{21} of the order of a few mΩs within the entire temperature range $\tau_{\rm tr}^{-1} > T > \tau_g^{-1}$, whereas the conventional theory would predict a rapid decay of the transresistivity from $\rho_{21} \sim 1$ mΩ at $T \sim \tau_{\rm tr}^{-1}$ to $\rho_{21} \sim 3\mu\Omega$ at $T \sim \tau_g^{-1}$.

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